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Reverberation-Limited Sonar Performance Predictions From Experimental Volume-Scattering-Strength Data

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24 February 1978

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PREFACE

This report describes work performed under NUSC Project No. A-650-02, "Underwater Acoustic/Environmental Data Bank for Sonar Design and Performance Prediction" (U), Principal Investigators, L. C. Maples, W. I. Roderick, and R. B. Lauer. Funding was provided under Task Area SF 52 552-007, Task 14315. The Program Manager was A. P. Franceschetti, Naval Sea Systems Command (SEA-06H1-4).

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Volume reverberation caused by biological scatterers often limits the effectiveness of active sonar systems. For sonar system modes that utilize the refractive properties of the ocean, not only volume scattering strength but also propagation loss to the scatterers varies significantly because of the nonuniform and changing vertical distributions of scatterers. Because the scatterers migrate and concentrate close to the ocean surface at night, the effect of these variations is particularly evident at that time for the surface duct and convergence zone (CZ) modes of sonar operation.

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Item 20. Abstract (cont'd)

In tests involving a mobile sonar platform and a research ship, detection performance estimates, based on measured propagation loss and reverberation levels, were computed for the mobile sonar system operating in CZ mode under volume-reverberation-limited conditions. Explosive sound sources and an omnidirectional hydrophone were used to measure integrated scattering strength (scattering strength of the water column) at the same time as propagation loss and sonar reverberation levels were being measured. In addition, the depth-dependent volume-scattering-strength profile was determined by using "upward- and downward-looking" transducers (source/receivers).

Actual system performance is compared with (1) measured propagation loss and the integrated scattering strength and (2) measured propagation loss and the complete volume-scattering-strength-versus-depth profile. For an accurate prediction of sonar system performance under refractive conditions, both the volume-scattering-strength profile and the propagation-loss profile are required.

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INTRODUCTION

Volume reverberation caused by biological scatterers often limits the effectiveness of active sonar systems. For sonar system modes that utilize the refractive properties of the ocean, significant variations in propagation loss and volume scattering strength are experienced because of the nonuniform and changing vertical distribution of scatterers. The layers of biological scatterers migrate and concentrate close to the ocean surface at night, so that the effect of these variations is particularly evident at that time for the surface duct and convergence zone (CZ) modes of sonar operation.

In a series of tests involving a mobile sonar platform and a research ship, detection performance estimates based on measured propagation loss and reverberation levels were computed for the mobile sonar system operating in the CZ mode under volume-reverberation-limited conditions. Explosive sound sources and an omnidirectional hydrophone were used to measure integrated scattering strength (also called the scattering strength of the water column) at the same time as propagation loss and sonar reverberation levels were being measured. In addition, the depth-dependent volume-scattering-strength profile was determined by using "upward- and downward-looking" transducers (source-receivers).

To predict sonar system performance under volume-reverberation-limited conditions, an accurate description of the acoustic and oceanographic inputs to the sonar equation is necessary. A review of the literature reveals that most measurements of volume scattering strength are obtained from explosive sources and are reported in terms of an integrated scattering strength.* Survey studies seldom report the complete volume-scattering-strength profile or give either the depth or the thickness of the scattering layer as a function of the resonance frequency of the biological scatterers. Therefore, with no depth-dependence information associated with the integrated scattering strength, the propagation loss to the scatterers causing the performance-limiting reverberation is usually assumed to be the same as the propagation loss to the target when system performance is being predicted. Further, the acoustic technique most often used in measuring the integrated scattering strength of the biological scatterers is not capable of resolving the vertical distribution of the scattering layers.

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*The integrated scattering strength measures the total effect from all scatterers within a unit-cross-section volume of the water column.

This report will demonstrate that, for an accurate prediction of sonar system performance under refractive conditions, both the volume-scattering-strength profile and the propagation-loss profile are required. The actual system performance, computed from measured propagation loss and reverberation levels, is compared with system performance predictions for a target at both shallow and moderate depths. The performance predictions were based on (1) measured propagation loss and the integrated scattering strength, and (2) measured propagation loss and the complete volume-scattering-strength-versus-depth profile.

Before the system performance predictions are considered, brief descriptions of the experimental procedures used in measuring the receiver depth- and range-dependent propagation loss, the sonar reverberation levels, and the volume-scattering-strength data are given. Then a comparison is made between the integrated data obtained from the explosive source and the integrated value derived from the volume-scattering-strength profile. The equations used in obtaining system performance estimates are given, and the predictions based on the scattering-strength data are compared with the results obtained from the measured reverberation levels.

EXPERIMENTAL PROCEDURE

The procedures used in the experiment under discussion for measuring CZ propagation loss and volume reverberation are summarized below.

The measurement of CZ propagation loss involved two ships. The source ship was equipped with a mobile sonar system and an expendable bathythermograph (XBT) system. The receiving ship was an oceanographic research vessel equipped with an "upward-looking" transducer mounted in a paraboloidal reflector, a hull-mounted transducer (dome), and a vertical hydrophone string (CZ array) that consisted of 20 hydrophones spaced at 25-ft (7.6-m) intervals. The hydrophone string was suspended from a spar buoy in such a way that the top and bottom hydrophones were located at depths of 60 and 535 ft (18.3 and 163 m), respectively. The hydrophones were "hard-wired" to the receiving ship, which maintained position by means of a bow thruster. The source ship began acoustic transmissions at an appropriate distance and, as the range was closed, the CZ moved slowly through the hydrophones. These joint operations are illustrated in figure 1.

An entire run was required to develop the propagation-loss curve as a function of receiver depth and range. The one-way propagation loss to each hydrophone was determined online with the general-purpose digital computer onboard the receiving ship. The exact time of acoustic transmission was transmitted by radio to the receiving ship, making possible

an accurate determination of acoustic travel time. This travel time was multiplied by the effective average horizontal sound speed (determined from on-site, deep, velocimeter data) to obtain the horizontal range between the ships.

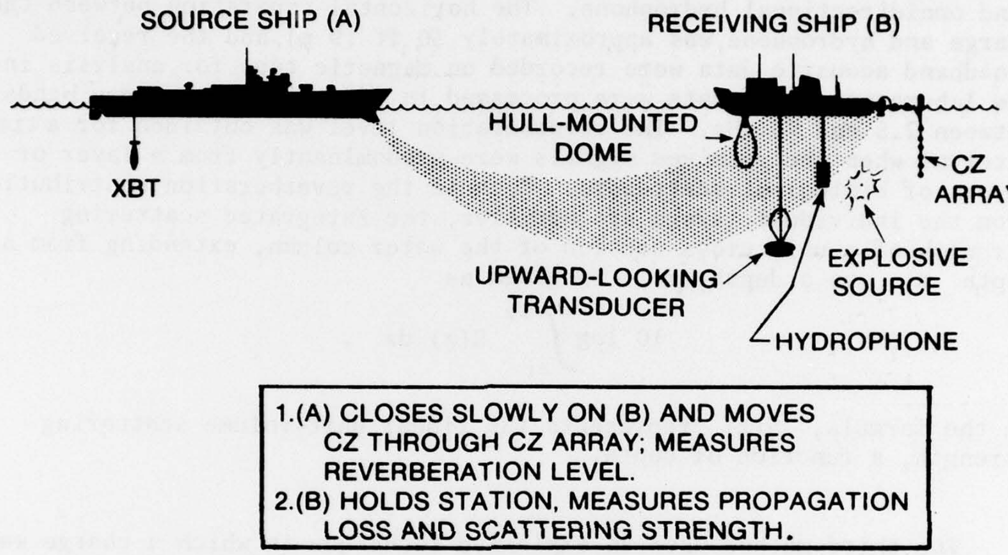

Figure 1. The Experiment

While the receiving ship was acquiring data and developing the profiles, the source ship was obtaining the CZ reverberation data measured by the sonar system. The reverberation data were digitally recorded and processed on the receiving ship computer between runs and after the operations to determine reverberation levels for signal-excess computations and for comparisons with CZ reverberation modeling. The zonal reverberation data acquired during the joint operations were obtained only during the stable periods of the biological scattering layer, i.e., around noon and midnight.

To obtain the volume scattering data, three methods were used. The first employed two directional transducers operating with short pulse lengths. One transducer was mounted inside a dome on the hull with its beam directed downward. Volume reverberation measured with this dome was contaminated by "ringing" for approximately the first 100 msec after each transmission. To offset this loss of data, the second transducer was deployed at a depth of 2000 ft (610 m) with its directional beam looking upward. The data from the two transducers were processed to yield values for scattering-strength-versus-depth profiles, with a depth resolution of 12.5 ft (3.81 m). These profiles, in terms of linear scattering strength, were then integrated with respect to depth to

obtain the integrated scattering strength. This result was compared with data derived from the following measurements.

The second set of experimental data was obtained by detonating several explosive charges at a depth of 60 ft, in proximity to a broadband omnidirectional hydrophone. The horizontal separation between the charge and hydrophone was approximately 30 ft (9 m), and the received broadband acoustic data were recorded on magnetic tape for analysis in the laboratory. The data were processed in 1/3-octave frequency bands between 2.5 and 20 kHz. The reverberation level was obtained for a time interval when the received signals were predominantly from a layer or layers of biological scatterers. Because the reverberation contributions from the individual layers are additive, the integrated scattering strength of a unit cross section of the water column, extending from a depth z_1 to a depth z_2, is given as

$$10 \log \int_{z_1}^{z_2} S(z)\, dz \quad .$$

In the formula, $S(z)$ represents the linear unit-volume scattering strength, a function of depth.

The third method used an explosive technique in which a charge was detonated close to an omnidirectional hydrophone, which was used to monitor the reverberation following the detonation. The measurements were made by using a variable-depth broadband explosive source and a receiving system that could be lowered to a maximum depth of 2500 ft (763 m). The scattering strength was determined as a function of frequency at discrete depths, and scattering strength versus depth profiles were constructed. These measurements were made only in the stable periods of the scattering layers to a maximum depth of 2000 ft (610 m) in order that the effects of layer migration during the sunrise and sunset transition periods would be minimized. The broadband data were recorded on magnetic tape and processed in the laboratory in 1/3-octave frequency bands at 4, 12.5, and 16 kHz.

Representative propagation-loss and volume-scattering-strength profiles, as measured, are shown in figure 2. It should be noted that, at the greater receiver depths, propagation loss increases although volume scattering strength decreases. Therefore, the major contributors to the reverberation level are the biological scatterers at the shallow depths. No significant increase in volume scattering strength was observed at depths greater than 500 ft (153 m). Also shown in figure 2 are the integrated volume-scattering-strength values that are used to generate signal-excess prediction curves. These data were obtained at night with the pulsed CW and the shallow-depth-explosive techniques previously mentioned.

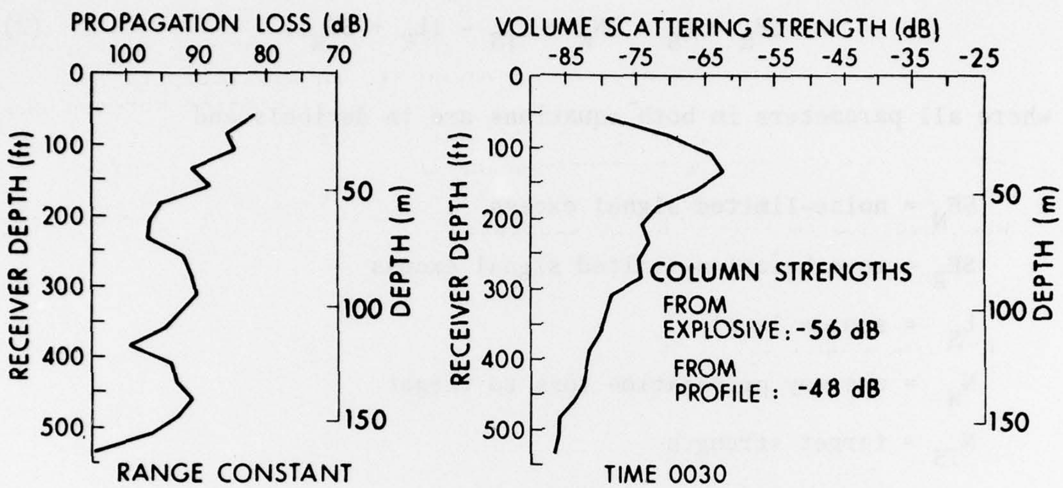

Figure 2. Depth-Dependent Propagation-Loss and Volume-Scattering-Strength Profiles

The scattering-strength profile was obtained by combining data from both upward- and downward-looking transducers. For comparison with the explosive data, the profile was integrated with respect to depth, resulting in an integrated scattering strength of -48 dB. The integrated scattering strength derived from the explosive data was -56 dB, 8 dB lower. The difference between these two values is attributed to the peak of the scattering layer at 130 ft (40 m) being in a shadow zone associated with the explosive measurements at this location. When the peak scattering strengths occur at greater depths or when more suitable near-surface isovelocity conditions exist, closer agreement is found between the data derived from these two measurements.

SONAR SYSTEM PERFORMANCE

The methods used to formulate estimates of sonar system performance are well known. The signal-excess formulation, based on the sonar equations, is used to estimate performance and is given in equations (1) and (2). For noise and reverberation backgrounds, we have

$$SE_N = L_S - 2N_W + N_{TS} - (L_N + SD_N) \quad (1)$$

and

$$SE_R = L_S - 2N_W + N_{TS} - (L_R + SD_R), \quad (2)$$

where all parameters in both equations are in decibels and

SE_N = noise-limited signal excess

SE_R = reverberation-limited signal excess

L_S = source level

N_W = one-way propagation loss to target

N_{TS} = target strength

L_N = self-noise level

L_R = reverberation level

SD_N = signal differential for noise

SD_R = signal differential for reverberation

$L_N + SD_N$ = noise-limited minimum detectable signal level

$L_R + SD_R$ = reverberation-limited minimum detectable signal level.

Signal excess indicates the amount of signal received in excess of that required for a 50 percent probability of detection and is a measure of the echo-to-background-interference ratio or level. Because the limiting interference background is either noise or reverberation or both, the total signal excess against a background composed of reverberation and noise is found by converting SE_N and SE_R to intensity ratios and adding in random phase. The total signal excess SE_T is given by

$$SE_T = -10 \log \left(10^{-SE_N/10} + 10^{-SE_R/10} \right) . \quad (3)$$

The total excess, given by equation (3), was used to predict the night-time system performance of the sonar system in the CZ mode.

PROPAGATION-LOSS INPUT TO SIGNAL-EXCESS EQUATIONS

As mentioned previously, the propagation loss was measured at 25-ft (7.6 m) intervals in receiver depth from 60 to 535 ft (18.3 to 163 m). The loss to the shallowest hydrophone represents the loss to a shallow target, and the loss to the deepest hydrophone represents the loss to a moderately deep target. The propagation-loss input to the signal-excess equation was based on a five-ping moving average of received intensities. Figure 3 shows the average propagation loss, measured across the zone, to the 60-ft and 535-ft hydrophones.

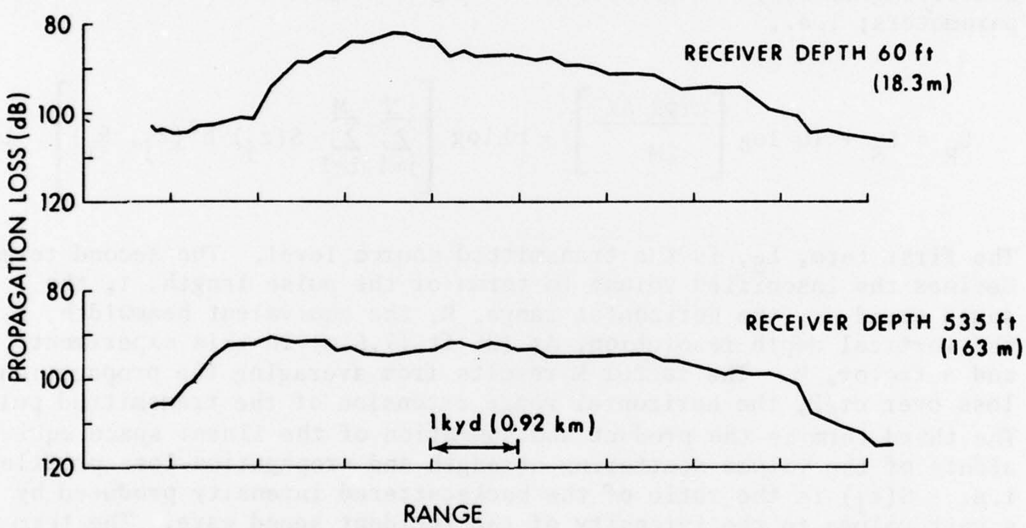

Figure 3. Average Propagation Loss Measured Across the Convergence Zone

REVERBERATION-LEVEL INPUT TO SIGNAL-EXCESS EQUATIONS

Except for the reverberation level, L_R, all the inputs to equations (1) through (3) have already been defined. For the comparison of system performance, the reverberation level measured by the sonar system will be used as a reference. Therefore, the system performance predictions computed from the volume-scattering-strength profile and from the integrated scattering strength will be compared with this reference.

The reverberation-level input to the signal-excess equation can be predicted from the volume-scattering-strength profile. The mathematical details for deriving the reverberation level can be found in volume 8 of the National Defense Research Committee (NDRC) Summary Technical Report, Physics of Sound in the Sea, 1946. The model computes the intensity of sound backscattered by a near-surface scattering layer by summing contributions from elemental scattering volumes that have associated depth-dependent volume scattering strength and propagation loss. Two of the primary inputs to the reverberation prediction model are the measured propagation-loss and volume-scattering-strength profiles. The propagation-loss values were measured by the 20-element hydrophone array and the volume scattering strength was measured by the upward- and downward-looking transducers. The predicted reverberation, given by equation (4), is in terms of the propagation loss to and from the scattering volume, the volume scattering strength, and the sonar system parameters; i.e.,

$$L_R = L_S + 10 \log \left[\frac{c\tau\Phi R\ \Delta z}{2M} \right] + 10 \log \left[\sum_{j=1}^{N} \sum_{i=1}^{M} S(z_j)\ h^2(z_j,\ R_i) \right]. \quad (4)$$

The first term, L_S, is the transmitted source level. The second term defines the insonified volume in terms of the pulse length, τ, the sound speed, c, the horizontal range, R, the equivalent beamwidth, Φ, the vertical depth resolution, Δz (25 ft (7.6 m) in this experiment), and a factor, M. The factor M results from averaging the propagation loss over $c\tau/2$, the horizontal range extension of the transmitted pulse. The third term is the product and summation of the linear space equivalents of the volume-scattering-strength and propagation-loss profiles; i.e., $S(z_j)$ is the ratio of the backscattered intensity produced by a unit volume to the intensity of the incident sound wave. The term $h(z_j,\ R_i)$, a function of depth, z, and range, R, is the loss in intensity from the source to the scattering volume.

The loss in intensity is related to the propagation loss by

$$N_W = \left[-10 \log h(z_j,\ R_i) \right] . \quad (5)$$

Because the deep refracted rays that form the CZ are confined to a narrow angular spread, vertical effects on source level have been neglected in this model. It also has been assumed that rays arriving at the convergence zone are nearly horizontal.

Predicted reverberation levels were computed using equation (4) and compared with values measured with the sonar system. Figure 4 shows

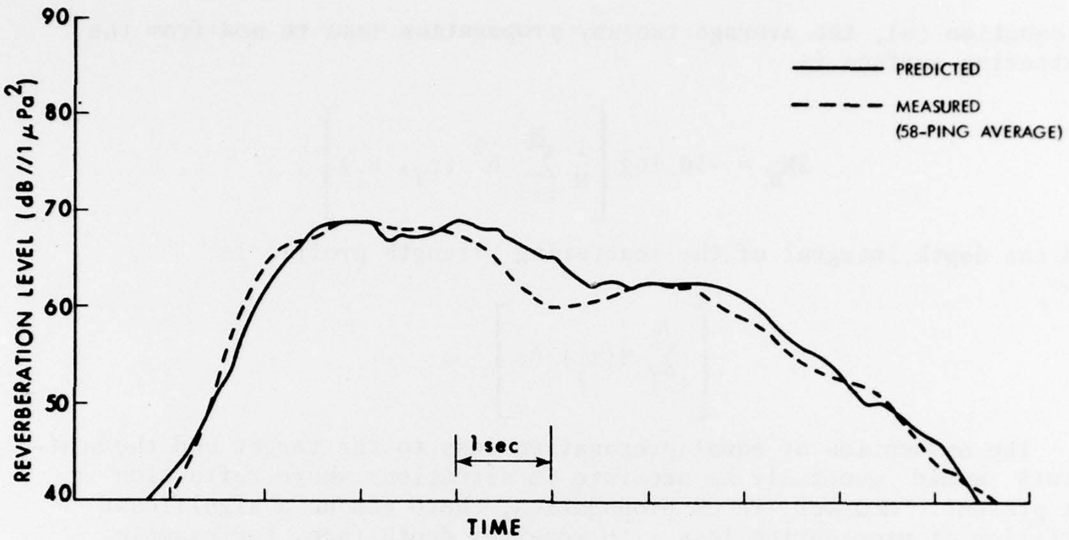

Figure 4. Measured and Predicted CZ Reverberation Levels for One Transmission

such a comparison; it was chosen to indicate the degree of agreement that can be achieved--in this case, the best sample obtained. Relative reverberation level is shown as a function of time for one sonar transmission. The measured levels are actually the mean values of intensity for 58 pings, converted to decibels. The volume scattering strength profile from which the calculated levels were derived was obtained at the time of the 42nd ping, at approximately midnight. The reverberation levels computed from the scattering strength profiles were used also in equation (2) to obtain system performance estimates.

In computing the reverberation level (and, hence, the signal excess) from an integrated scattering strength, it is commonly assumed that (1) the propagation loss to the scatterers is the same as that to a target positioned at a depth z_T, (2) the projection of the pulse length on the scattering surface is short compared with the projection of the vertical beamwidth of the source-receiver, (3) the horizontal range-extension of the transmitted pulse is short compared with the range to the scattering surface, and (4) the arrival angles of the CZ rays are nearly horizontal. When the above assumptions are used, the reverberation level is

$$L_R = L_S + 10 \log \left[\frac{1}{M} \sum_{i=1}^{M} h^2 (z_T, R_i) \right] + 10 \log \left[\sum_{j=1}^{N} S(z_j) \Delta z \right] + 10 \log \left[\frac{c\tau\Phi R}{2} \right] . \quad (6)$$

In equation (6), the average two-way propagation loss to and from the scattering surface is

$$2N_W = -10 \log \left[\frac{1}{M} \sum_{i=1}^{M} h^2 (z_T, R_i) \right] ,$$

and the depth integral of the scattering strength profile is

$$\left[\sum_{j=1}^{N} S(z_j) \Delta z \right] .$$

The assumption of equal propagation loss to the target and the scatterers would generally be accurate in situations where refraction is not present. However, in CZ propagation, there can be a significant variation of propagation loss with receiver depth (see, for example, figure 2). The degree of inaccuracy suffered when the integrated scattering strength is used depends on the difference between the propagation loss to the assumed target depth and to the actual target depth of the scattering layer. Because the difference is double as a result of the two-way propagation condition, this difference can be the major contributor to signal excess inaccuracies. Substituting equation (4) into the reverberation-limited signal-excess equation yields

$$SE_R' = N_{TS} + 10 \log \left[\frac{1}{M} \sum_{i=1}^{M} h^2(z_T, R_i) \right] - 10 \log \left[\frac{c\tau R\Phi \Delta z}{2M} \right]$$
$$- 10 \log \left[\sum_{j=1}^{N} \sum_{i=1}^{M} S(z_j)\, h^2(z_j, R_i) \right] - SD_R \quad ,(7)$$

when the signal excess is computed from the scattering-strength profile.

The reverberation-limited signal excess computed from the integrated scattering strength can be found by substituting equation (6) into equation (2), which yields

$$SE_R = N_{TS} - \left\{ 10 \log \left[\sum_{j=1}^{N} S(z_j) \Delta z \right] + 10 \log \left[\frac{c\tau R\Phi}{2} \right] \right\} - SD_R \quad . \qquad (8)$$

A qualitative comparison of the signal-excess predictions obtained from the depth-dependent volume-scattering-strength profile and from the integrated scattering strength can be made by computing the differences

in signal excess; that is,

$$\Delta SE_R = SE_R - SE_R' = 10 \log \left[\frac{\sum_{i=1}^{M} \sum_{j=1}^{N} S(z_j)\, h^2(z_j, R_i)}{\sum_{i=1}^{M} h^2(z_T, R_i) \sum_{j=1}^{N} S(z_j)} \right] . \quad (9)$$

From equation (9), it can be seen that the difference in signal-excess predictions is zero when the propagation loss is constant over the scattering volume. In general, if the propagation loss is not constant over the scattering volume and the signal excess is computed from the integrated scattering strength, the signal-excess prediction will be as follows:

- Overly optimistic for the propagation loss computed to deep targets in the CZ; that is,

$$\sum_{i=1}^{M} h^2(z_T, R_i) \sum_{j=1}^{N} S(z_j) < \sum_{i=1}^{M} \sum_{j=1}^{N} S(z_j)\, h^2(z_j, R_i) . \quad (10)$$

- Overly pessimistic for propagation loss computed to shallow targets; that is,

$$\sum_{i=1}^{M} h^2(z_T, R_i) \sum_{j=1}^{N} S(z_j) > \sum_{i=1}^{M} \sum_{j=1}^{N} S(z_j)\, h^2(z_j, R_i) . \quad (11)$$

A quantitative comparison of the signal-excess predictions based on the volume-scattering-strength profile and on the integrated value of -48 dB obtained from the profile has been made. It should be noted that no significant increase in the integrated scattering strength results from contributions at depths greater than 500 ft (153 m). In figures 5 and 6, the total signal-excess predictions (equation (3)) based on the volume-scattering-strength profile and the integrated scattering strength derived from the profile are compared with the performance prediction derived from the measured reverberation data. The comparison is shown for targets at depths of 60 ft (figure 5) and 535 ft (figure 6). It can be seen that there is good agreement, at both target depths, between measured performance and the performance predictions based on the volume-scattering-strength profile.

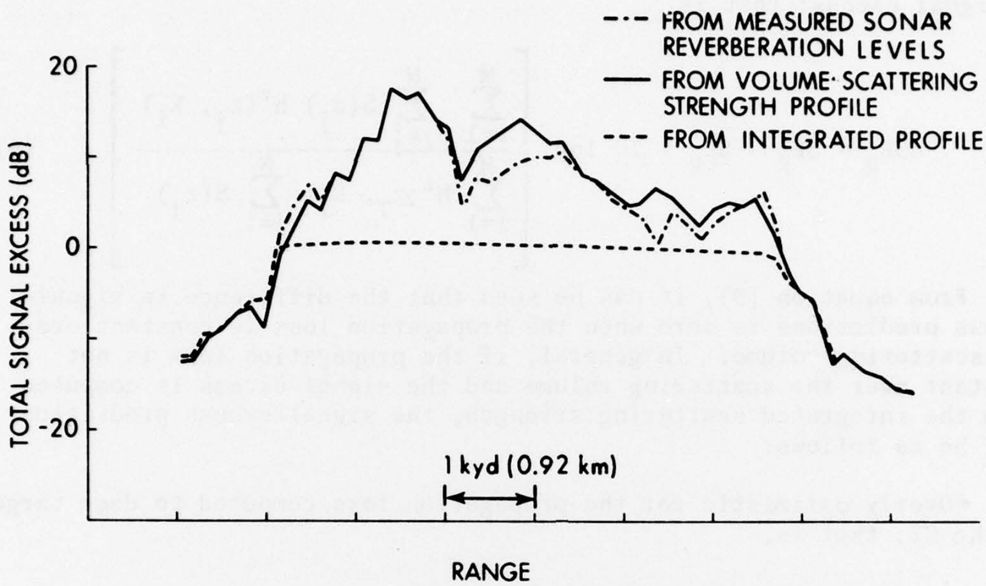

Figure 5. Comparison of Signal-Excess Predictions For a Shallow Target

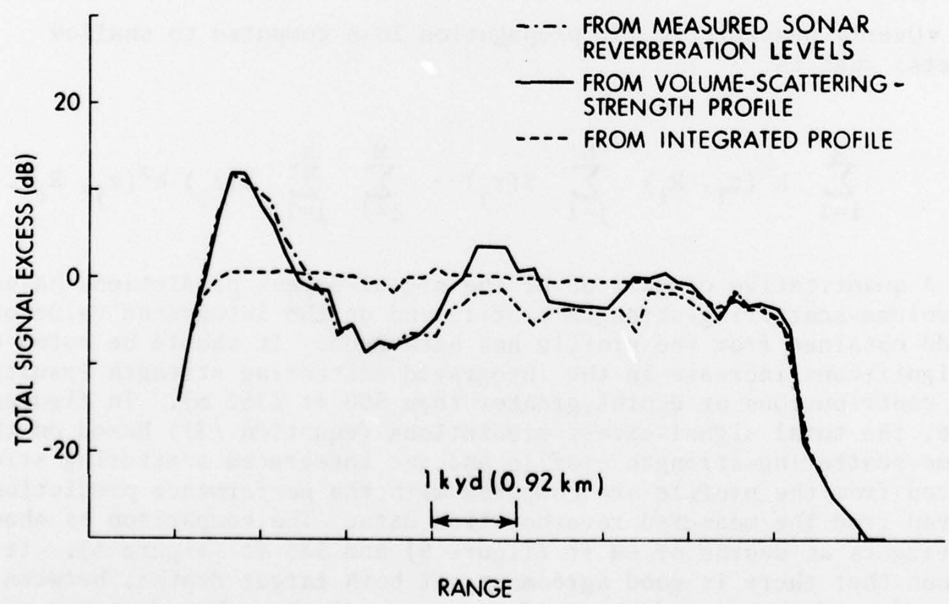

Figure 6. Comparison of Signal-Excess Predictions For a Target at Moderate Depth

As expected, the performance predictions based on the integrated scattering strength are invariant with respect to target depth and grossly underestimate the performance capability of the mobile sonar to detect shallow targets. For the deep target depth, there is an initial detection capability for a zonal width of approximately 1 to 2 kyd (0.9 to 1.8 km), which cannot be predicted from the integrated scattering strength. This initial detection capability is a result of the decrease in propagation loss at the deeper depths as the CZ rays are refracted toward the surface. Moreover, although the scatterers are located at a shallow depth, they are initially in a high propagation loss region; therefore, the effect of any volume reverberation is minimal. Thus, there will be a small zone over which a good detection capability exists before the onset of CZ reverberation.

SUMMARY AND CONCLUSIONS

This report has analyzed predictions of sonar system performance for convergence zone (CZ) operation under volume-reverberation-limited conditions. Predictions of signal excess obtained from both depth-dependent volume-scattering-strength profiles and integrated scattering strengths have been compared with signal excess predictions calculated from measured reverberation levels and propagation loss. These performance predictions were generated for targets at both shallow (60 ft, 18.3 m) and moderate (535 ft, 163 m) depths. The comparison of measured-parameter predictions with the predictions generated from the volume-scattering-strength profile yielded excellent agreement for both depths. However, errors as large as 10 to 15 dB were observed for the predictions obtained from the integrated scattering strength when neither the depth nor the thickness of the scattering layers was specified. These errors are primarily a result of the difference between the propagation loss to the assumed target depth and the propagation loss to the depth of the scattering layer.

Because all active sonar systems are affected by biological scattering in CZ, surface duct, bottom-bounce, and reliable acoustic path (RAP) modes of propagation, it is the conclusion of this report that, for those system modes affected by refraction, the volume-scattering-strength profile and the depth-dependent propagation loss must be incorporated into reverberation models to accurately predict sonar system performance.

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